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A Comparison of Vacuum Infusion, Vacuum Bagging, and Hand Lay-Up Process on The Compressive and Shear Properties of GFRP Materials

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Abstract

Fiber-reinforced plastics are widely used in aerospace, marine, military, automotive, wind turbine, sports, and civil engineering applications. GFRP is a common material used in engineering applications such as for UAV structural material. Several techniques that can be used in the composite structure manufacturing process are HLU, VB, and, VARI. This paper studies the influence of the three manufacturing processes on the compressive and shear properties of GFRP composites. This study uses e-glass fiber as reinforcement material and a clear epoxy polymer called lycal as matrix material. The composites were manufactured by using HLU, VB, and VARI processes. The specimen dimensions, compressive, and shear tests are following ASTM standards. The microstructural characteristics were observed using a scanning electron microscope. The compressive strength of VARI composite is higher than HLU and VB composites up to 71% and 53%, respectively. The shear strength of the VARI composite is higher than HLU and VB composites up to 71% and 53%, respectively.

Keywords: *fiber-reinforced plastics; GFRP; UAV; composite; VARI.*

1. Introduction

The application of fiber-reinforced plastic has grown in the aerospace industry to replace metal materials (Aryaswara et al., 2022; Bulgakov et al., 2018; Gajjar et al., 2020; Komarov et al., 2015; Verma et al., 2014). Its use has also increased in the marine, military, automotive, wind turbine, sports, and civil engineering industries (Kim et al., 2014; Kumar & Kumar, 2021; Mazzuca et al., 2022; van Oosterom et al., 2019; Xu et al., 2017; Zarei et al., 2022). This is due to its high specific stiffness, strength and modulus, reliability, dimensional stability, temperature resistance, corrosion resistance, fatigue resistance, wear resistance, chemical resistance, and high impact resistance (Abdurohman et al., 2018; Aryaswara et al., 2022; Gajjar et al., 2020; Kim et al., 2014; Komarov et al., 2015; Mazzuca et al., 2022; Obande et al., 2019; Sunilpete & Cadambi, 2020; Toldy et al., 2020; Verma et al., 2014; Xu et al., 2017; Zarei et al., 2022).

Several techniques can be used in the process of making composites with liquid resin and dry fibers. These techniques include vacuum infusion (VI), vacuum bagging (VB), and wet hand lay-up (HLU). These three manufacturing processes can be applied in all types of composite products depending on the expected strength and surface finish requirements. For example, in the composite ship industry, there are manufacturers that use HLU technology, while other manufacturers use VB technology, and some even use VI technology. HLU is the simplest technique, followed by vacuum bagging by adding peel-ply, breather, bagging film, and a vacuum pump to compress the fiber layers. Vacuum infusion utilizes vacuum pressure from a vacuum pump to circulate liquid resin into the lamination area. The Advantage of HLU is simplest and cheapest technique. On the other hand the HLU has dissadvantage on the less flatness of composite surface result. The second technique is vacuum bagging that has better surface quality than HLU but more expensive and more complexity than HLU. The last method is Vacuum infusion that is needed not only extra equipments but also extra times of preparation. Although VI is the most expensive technique but that give the best result of composite surface. The vacuum infusion process has received increasing attention because of its ability to produce large composite structures with excellent mechanical properties (Kim et al., 2014).

There are several variants of the composite manufacturing process using the vacuum infusion technique. The commons of these techniques are Vacuum Assisted Process (VAP), Vacuum Assisted Resin Infusion (VARI), Seemann Composites Resin Infusion Molding Process (SCRIMP), Vacuum Assisted Resin Transfer Molding (VARTM), and so on (van Oosterom et al., 2019; Verma et al., 2014). VARTM first pioneered in 1950, is the simplest form of resin infusion, without a resin distribution medium to aid wetting (van Oosterom et al., 2019). SCRIMP was first patented in 1990 by Seemann Composites Inc. and is the most widely applied liquid resin infusion technique. This technique is similar to VARTM but with the addition of a flow medium to help the resin flow over the laminate surface and further reduce the wetting time (van Oosterom et al., 2019). VARI is a composite manufacturing technique similar to SCRIMP. VAP is a liquid resin infusion technique using a semi-permeable membrane to enable degassing of the lamination area to a translucent thickness and minimize the likelihood of resin locking, producing in a wide-scale dry point developed by EADS/Airbus (Bodaghi et al., 2020; van Oosterom et al., 2019). The aircraft industry has now invented the vacuum infusion process in producing wing covers, as in the example of the Bombardier CSeries (now the Airbus A220) (Hindersmann, 2019).

1.1. Previous Research

Previous studies studied the effect of using vacuum infusion, vacuum bagging, and wet hand lay-up techniques on the tensile properties of GFRP composites. The results of previous studies showed that the vacuum infusion composite's tensile strength was higher than wet HLU and VB (Abdurohman et al., 2018). Another study on GFRP composites was conducted by Kim, et al. 2014 by comparing two composite fabrication techniques: hand lay-up and vacuum infusion. The study results showed that the tensile strength of the vacuum infusion composite was higher than that of the hand lay-up composite. However, the compressive and shear strengths are only 16 MPa and 6 MPa different from those of the composite hand lay-up (Kim et al., 2014). A study of the influence of composite manufacturing techniques was also carried out on carbon composites on the flame retardancy of the composites. The manufacturing technology used is HLU followed by hot pressing and vacuum infusion. The results show that the VI composite is better than the HLU followed by hot pressing (Toldy et al., 2020).

GFRP is a common composite material used in engineering applications, including as a UAV (unmanned aerial vehicle) structural material. The commonly used GFRP manufacturing technique for UAV structure is the wet hand lay-up. VB and VARI are manufacturing techniques with liquid resin to improve the mechanical properties of fiber-reinforced plastic materials. Before applying it for the manufacturing of UAV parts, it is necessary to know the mechanical properties of GFRP resulting from several manufacturing technologies. This is necessary to carry out a structural analysis of the UAV before the actual part manufacturing process.

Because the tensile properties of GFRP with various manufacturing techniques HLU, VB, and VARI have been evaluated in previous studies (Abdurohman et al., 2018), it is necessary to know other mechanical properties such as compressive and shear properties. The objective of this paper is to determine the comparison of compressive and shear properties of GFRP manufactured by HLU, VB, and VARI. The advantage of this study compared to other study is that it can obtain more complete material properties data for the three composite manufacturing processes where other researchers only used two manufacturing processes in their research, namely HLU and VI. This study is expected to know the best manufacturing techniques for the fabrication of the structure of UAV composite. This study uses e-glass fiber as reinforcement and clear epoxy resin commercially named lycal as a matrix. The mechanical properties and microstructural characteristics are investigated.

2. Methodology

2.1. Materials

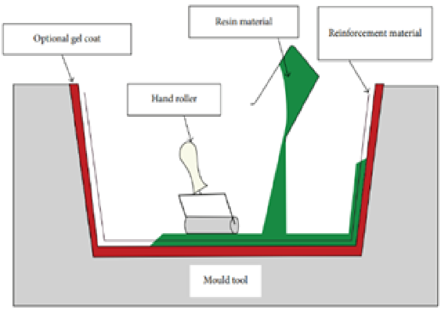
Woven cloth e-glass fabric commercially named fiber cloth EW-185 and a hard type resin with low viscosity commercially named lycal 1011 were used as reinforcement and matrix in this experiment. The e-glass fiber used in this study was 185 gsm and was purchased from Justus Kimia Raya. Lycal 1011 is a hard-type two-pack polymer consisting of Part A and Part B with a mixing ratio of 3:1 and was purchased from the commercial market. It is applicable for fabricating process of composite by vacuum-assisted resin infusion (VARI), vacuum bagging (VB), and hand lay-up (HLU) techniques.

(a) (b) (c)

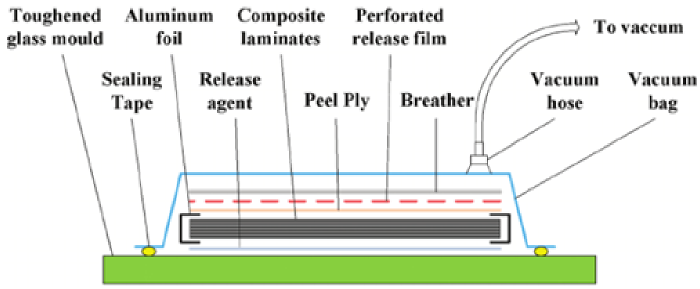
Figure 2-1. Lycal resin and hardener (a), glass fabric (b), and vacuum pump (c)

2.2. Fabrication Process

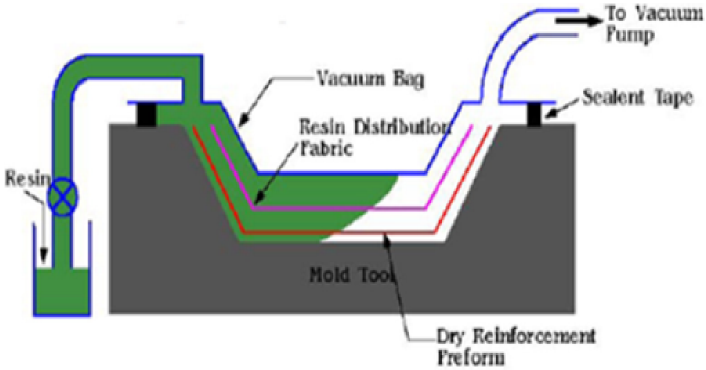
The fiber-reinforced plastics were produced using three different manufacturing techniques of composite. They are vacuum-assisted resin infusion (VARI), vacuum bagging, and manual hand lay-up. The e-glass/lycal composite panels have the same stacking sequence of fiber cloth EW-185 for each manufacturing technique. The composites consist of 25 plies of e-glass for compressive specimens and 24 plies of e-glass for shear specimens. HLU is an open mold technique and the simplest manufacturing technique of composite where the work is done manually. The liquid resin is applied to the fibers evenly using a brush for each fiber layer. After the last fiber layer, the composite laminate is left for 24 hours to cure. The skill and accuracy of workers greatly affect the final composite result. The final thickness of the composite cannot be controlled and is largely determined by the stresses during the lamination process.



(a) hand lay-up (Udupi & Lester Raj Rodrigues, 2016)



(b) vacuum bagging (Ismail et al., 2019)

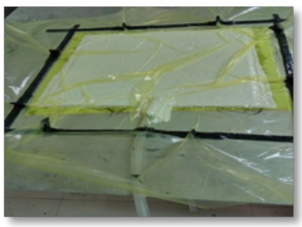


(c) vacuum infusion (Kumar & Kumar, 2021)

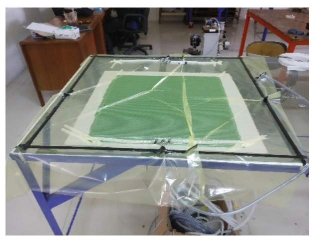
Figure 2-2. HLU, VB, and VI process

VB technique uses plastic bagging to cover the laminated area on the mold for making composites and is a continuation of the hand lay-up process. After all layers of fiber and resin have been laminated using a brush, the lamination area is closed using peel-ply, breather, and plastic bagging. Plastic bagging is provided with holes and connected to a vacuum pump using a hose to suck the air into the laminate area. This process is expected to draw air trapped during the lamination process and remove excess resin so that the composite results are better. The vacuum pump remains on until the resin gels and remains under vacuum for 24 hours until the composite cures.

(a)



(b)



(c)

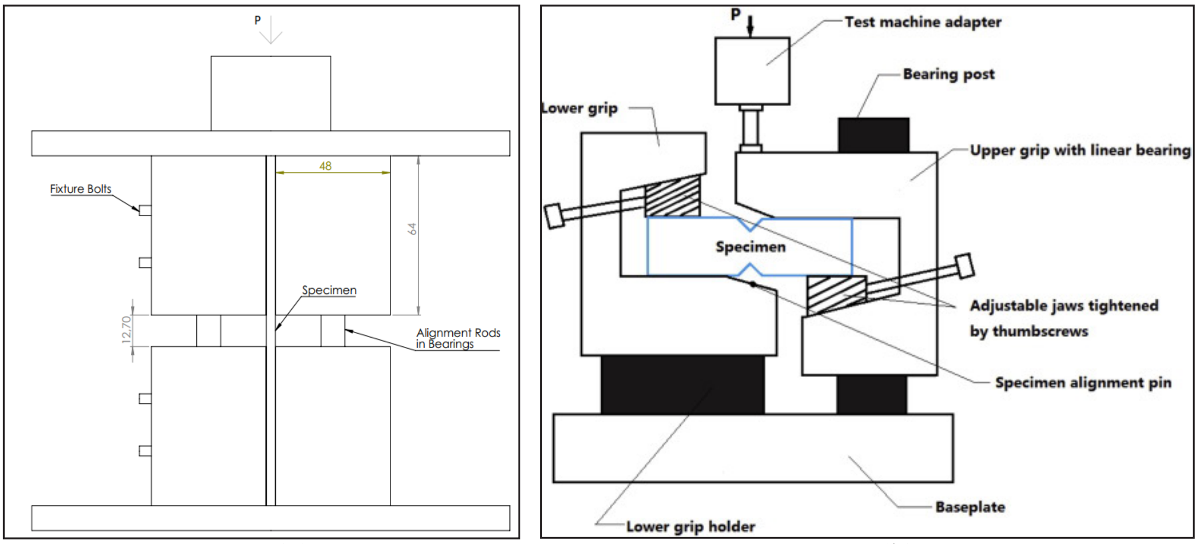
Figure 2-3. Hand Lay-up (a), vacuum bagging (b), and VARI (c) techniques

The VARI method utilizes a vacuum pressure from a vacuum pump to flow resin to the laminated area of the fibers. When the vacuum condition has been reached, the resin is flowed from the resin reservoir through the inlet tube to the laminate area until the fiber area is completely wetted. Keep the vacuum condition until the resin forms a gel. The composite panels were cured for 24 hours at ambient temperature.

The fiber-to-resin ratio by mass of HLU, VB, and VARI process are 61:39, 74:26, and 41:59 respectively. The test specimens were cut from composite panels according to the recommendation dimensions of ASTM D6641 and D5379 for compressive and v-notched shear tests respectively.

2.3. Mechanical Tests

The compressive and shear tests were performed using the Universal Testing Machine Tensilon 100 kN in Research Center for Aeronautics Technology BRIN. The compressive tests were investigated according to ASTM D6641 standards using a special fixture for compressive tests. The specimen dimension for the compressive test was 140 mm in length, 12 mm in width, and 5 mm in thickness. The v-notched shear tests have been evaluated as per ASTM D5379. The specimen dimension can be seen in Fig. 2-5. There are five specimens of each variation of manufacturing technique and the compressive and v-notched shear properties values were evaluated.



(a) (b)

Figure 2-4. Compressive test (a), shear test (b)

The compressive test is carried out using a special fixture as shown in Fig. 2-4 (a). The compressive test specimen is installed in the fixture then the fixture is placed in the UTM test area. Loading is done by providing a compressive load (P) with a constant speed of 1.3 mm/ minute. Loading is carried out continuously until the specimen fails. The load value received by the specimen is read by the load cell and recorded continuously by the software installed on the UTM. Compressive strength (F^c) is calculated using Eq. (2-1) where P^c is the maximum load to failure (N), w is the width of the specimen (mm), and h is the thickness of the specimen (mm).

$$F^c = P^c/(\mathrm{w} \times \mathrm{h}) \quad (2\text{-}1)$$

The v-notched shear test specimens are made as shown in Fig. 2-5 and the v-notched shear testing process is carried out using a special fixture as shown in Fig. 2-4 (b). The v-notched shear test specimen is installed in the fixture then the fixture is placed in the UTM testing area. Loading is done by providing a load (P) with a constant speed of 2 mm/minute. Loading is carried out continuously until the test object fails. The load value received by the specimen is read by the load cell and recorded continuously by the software installed on the UTM. Ultimate shear strength (F^s) is calculated using Eq. (2-2) where P^s is the maximum load to failure (N) and A is the cross-sectional area (mm2). A is calculated using Eq. (2-3) where w is the width of the specimen in the v-notched area and h is the thickness of the specimen.

$$\mathrm{F} = \mathrm{P}/\mathrm{A} \quad (2\text{-}2)$$

$$\mathrm{A} = \mathrm{w} \times \mathrm{h} \quad (2\text{-}3)$$

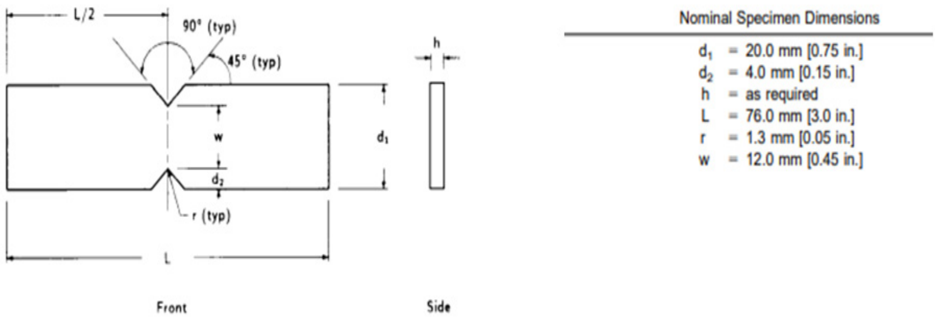


Figure 2-5. The v-Notched shear test specimen

2.4. SEM (Scanning Electron Microscopy) Observations

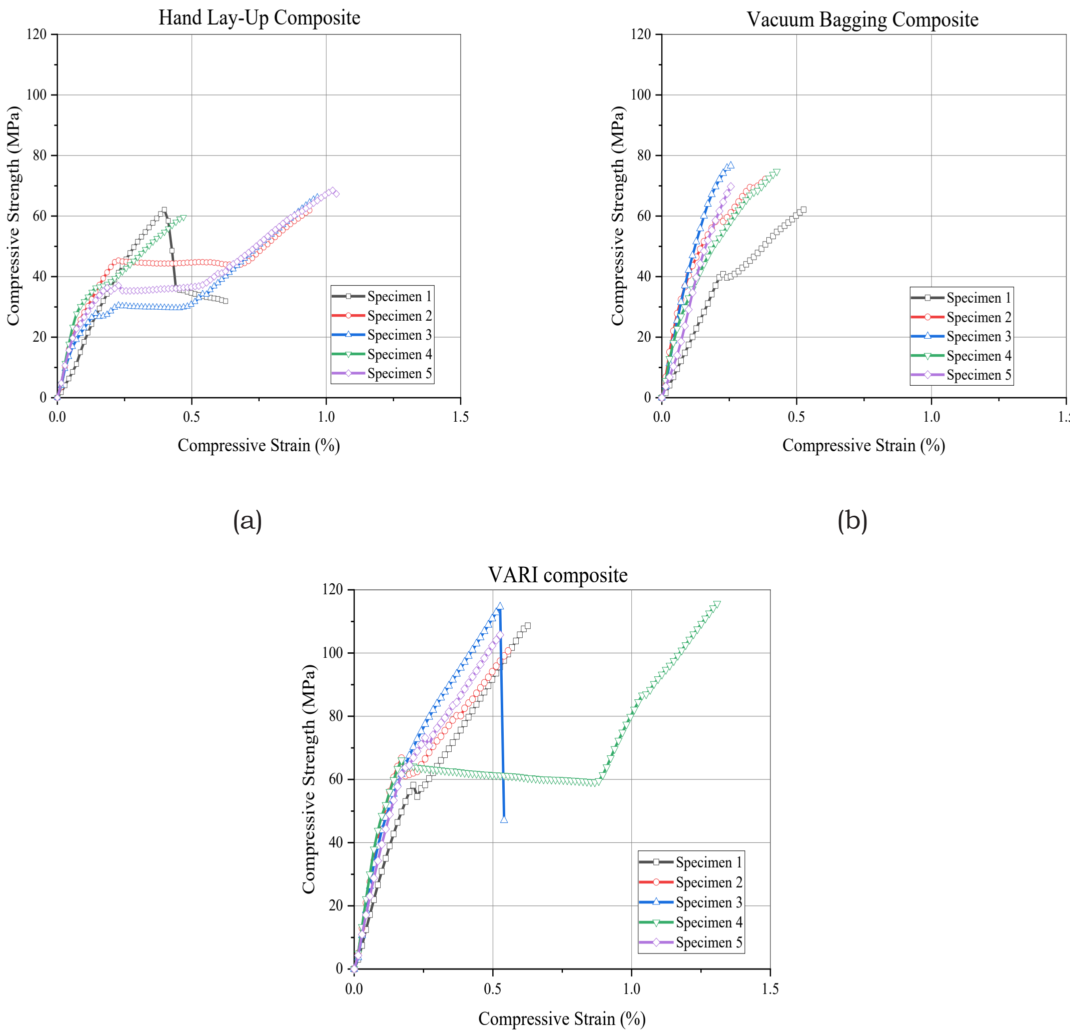
The micrograph characterization was investigated by SEM in a previous study. Inspect S50-AMETEX was used to investigate the interfacial characteristics of the composite. The fracture morphology of the sample can be seen at certain magnification images.

3. Result and Analysis

3.1. Compressive Properties

Figures 3-1 (a), (b), and (c) represent the compressive stress vs strain curve of glass/lycal composite for HLU, VB, and VARI processes, respectively. Figure 3-1 shows that the compressive stress vs strain curves for the three composites are typical, but differ in their slopes and stress peaks. The slope of the VB composite looks steeper and the peak points are higher than the HLU composite. This indicates that the VB composite is stiffer and stronger than the HLU composite. However, the slope of the VARI composite curve is steeper and the peak points are higher than the HLU and VB composites. This shows that the VARI composite is stiffer and stronger than the other two composites.

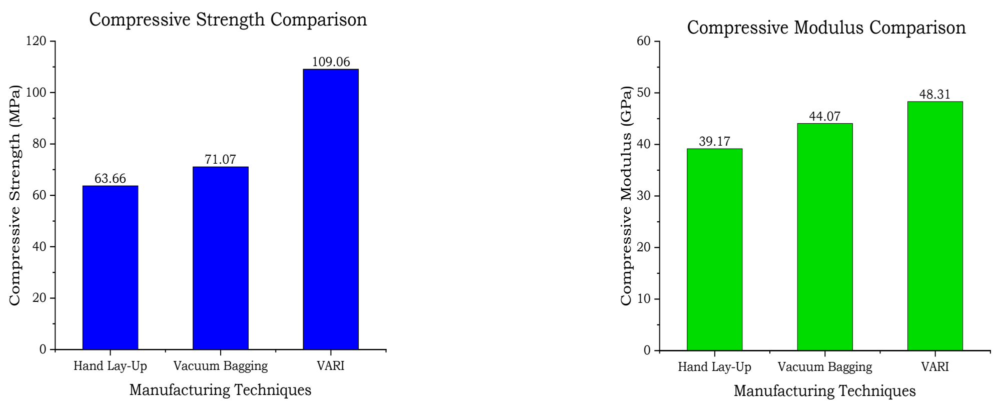
Figure 3-2 illustrates the evaluation of compressive modulus and strength of HLU, VB, and VARI specimens. Fig. 3-2(a) exhibits that the compressive strength of hand lay-up composite is the lowest compared to vacuum bagging and VARI composites. The compressive strength of the VB composite is higher than the HLU composite up to 12% but lower than the VARI composite. The compressive strength of the VARI composite is superior to HLU and VB composites. The compressive strength of the VARI composite is 71% higher than the HLU composite and 53% higher than the VB composite. The average compressive strength of HLU, VB, and VARI composites are 63.66 MPa, 71.07 MPa, and 109.06 MPa respectively. The study's findings demonstrate that the trend of compressive modulus is similar to that of compressive strength but with a different value. The compressive modulus of the VB composite is 13% higher than the HLU composite. The compressive modulus of the VARI composite is 23% higher than the HLU composite and 10% higher than the VB composite. The average compressive modulus of HLU, VB, and VARI composites are 39.17 GPa, 44.07 GPa, and 48.31 GPa respectively. According to these findings, the compressive strength and modulus of the VARI composite are the highest among the three types of composites. This is similar to previous studies on the tensile properties of the glass/lycal composite with HLU, VB, and VARI processes. The previous study's findings demonstrate that the VARI composite's tensile strength and modulus are superior to those of the HLU and VB composites. These results indicate that the use of the VARI composite manufacturing technique produces composites with better tensile and compressive properties than HLU and VB.



(a) (b)

(c)

Figure 3-1: Compressive stress-strain curve of (a) HLU, (b) VB, and (c) VARI composites

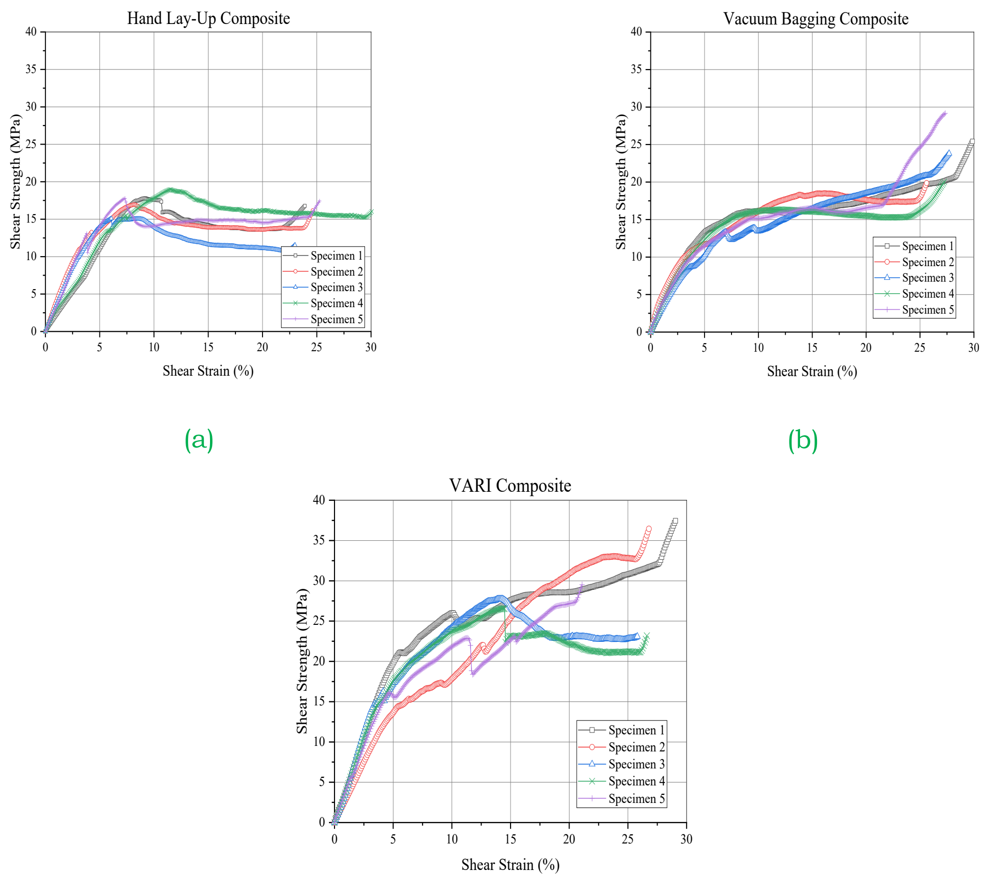


(a) (b)

Figure 3-2: Compressive strength (a) and modulus (b) comparison

3.2. Shear Properties

Figures 3-3 (a), (b), and (c) represent the v-notched shear stress vs strain curve of glass/ lycal composite for HLU, VB, and VARI techniques, respectively. Figure 3-3 shows that the v-notched shear stress vs strain curves for three composites are typical, with almost the same slope but different stress peaks or ultimate shear strength (USS). The determination of the point of the USS is different from the ultimate tensile and compressive strength. ASTM D5379 states that if the shear strain on the stress vs strain curve is more than 5%, then the USS value used is the grade at 5% strain. This shows that the value of the USS of the composite is not at the highest point of the curve. So that the average values of the shear strength of the HLU, VB, and VARI composites at 5% strain were 13.06 MPa, 11.88 MPa, and 16.88 MPa respectively as shown in Fig. 3-4(a).



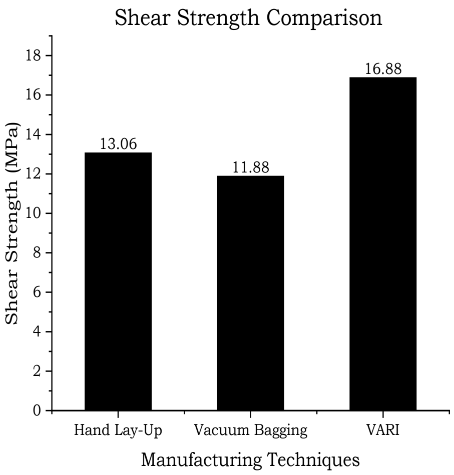
(a) (b)

(c)

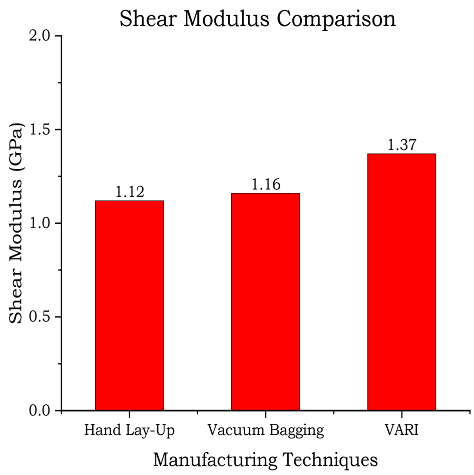
Figure 3-3: Stress-strain curve for v-notched specimens of (a) HLU, (b) VB, and (c) VARI composites

Figure 3-4 compares the data in v-notched shear strength and modulus of HLU, VB, and VARI composites. Fig. 3-4(a) exhibits that the v-notched shear strength of HLU and VB composites is not much different. The difference between the two is about 9%. Nevertheless, this value indicates that the shear strength of the VB composite is lower than that of HLU, in contrast to the compressive strength and tensile strength in previous studies which had higher values. There are two possible causes of this. The first possibility is the nature of the material itself where the VB process does not always produce better v-notch shear properties than HLU in contrast to tensile and compressive properties. The second possibility is the VB manufacturing process which has an uneven compaction process. To prove the most influential possibility, further studies are needed on different composite materials from the composites used in this study as well as a longer VB process. Meanwhile, the VARI composite outperformed the HLU and VB composites in terms of v-notched shear strength by 29% and 42% respectively. This indicates that the VARI composite's shear strength is superior to HLU and VB composites. Figure 3-4(b) also indicates the highest shear modulus of the VARI composite. There was no significant difference between the shear modulus of the HLU and VB composites, which was 4%. The shear modulus of the VARI composite is 22% higher than the HLU composite and 18% higher than the VB composite. The average shear modulus of

HLU, VB, and VARI composites are 1.12 GPa, 1.16 GPa, and 1.37 GPa respectively. These results exhibit that the VARI composite's shear modulus and strength are the highest among the three types of composites. The results of these shear properties support the results of the previous tensile and compressive properties that the use of the VARI composite manufacturing technique produces composites with superior mechanical properties than the HLU and VB techniques. The results of current and previous studies show that the use of the VARI composite fabrication technique is very beneficial for application in the manufacture of engineering structures such as Unmanned Aerial Vehicles (UAV) or others because of its better mechanical properties than HLU and VB.



(a)



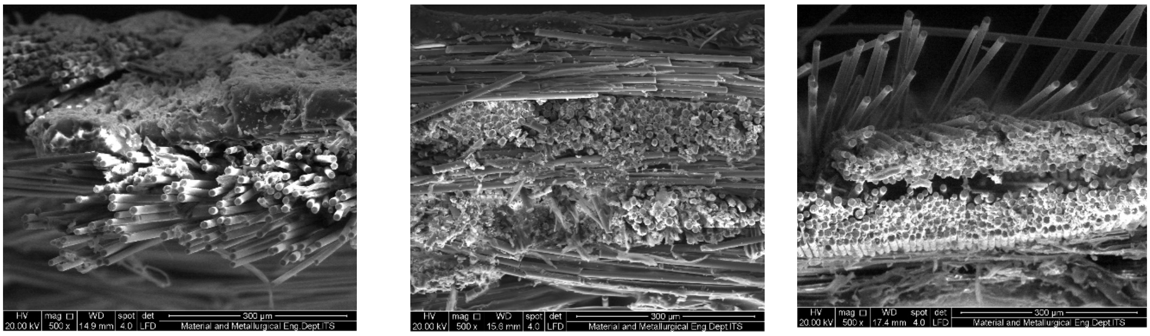
(b)

Figure 3-4: Shear strength (a) and modulus (b) comparison

3.3. SEM

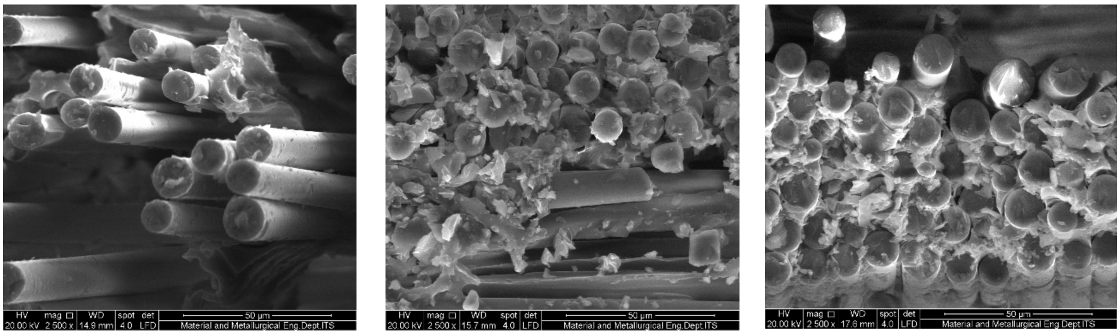
SEM was carried out in previous studies to see the fracture surface of damaged composite specimens. SEM was performed on the fracture surface of the tensile testing specimen. SEM is applied to specify the features of the fiber and resin seen in the specimen fracture to support the analysis of mechanical test results. Figures 3-5 (a), (b), and (c) show a comparison of HLU, VB, and VARI composite SEM photographs with a magnification of 500. The SEM results show that the HLU and VB composites have resin-rich areas with different thicknesses as shown in Figures 3-5 (a) and (b). The resin-rich area in the VB composite is thinner than the HLU composite. This shows that VB's manufacturing results are better than HLU's because it uses vacuum pressure in the final process so that the laminate is pressed and the resin is spread more evenly even though there is still a thin layer rich in resin on the surface. This resin-rich area affects the strength of the composite because the resin which is supposed to bind the fibers into the composite becomes concentrated in one area and some fibers are less bonded by the resin. This causes the more areas rich in resin, the lower the strength of the composite because there is a load that is only held by the resin where the strength of the resin is much lower than that of the fiber. However, SEM photos do not show any portion of the VARI composite that is resin-rich as shown in Figure 3-5 (a). This indicates that the VARI technique's composite manufacturing results are better than HLU and VB because this technique uses vacuum pressure from the beginning to the end of the process to flow the resin to wet the fibers without any manual lamination process.

Figures 3-6 (a), (b), and (c) show a comparison of HLU, VB, and VARI composite SEM photographs with a magnification of 2500. The SEM photo results show that almost all the fibers on the fracture surface of the HLU composite are detached from the matrix as seen in Figure 3-6 (a). This shows the weak connection between the matrix and the fiber in the HLU composite. This weak fiber/matrix bond causes the strength of the composite to be lower. This is because the function of the matrix is to transfer the load received by the composite to all the fibers in it. So the weaker the fiber/matrix bond, the smaller the load that can be accepted by the composite. Meanwhile, on the fracture surface of the VB composite, it can be seen that many fibers are still well bound to the matrix, although there are a few fibers that are detached from the matrix, as shown in Figure 3-6 (b). Figure 3-6 (c) shows that almost the surface of the fracture, including every fiber of the VARI composite specimen still appears to be well bound to the matrix. This proves that the VARI composite fiber-matrix bond is better than the HLU and VB composites.



(a) HLU (b) VB (c) VARI

Figure 3-5: SEM micrograph magnitude 500x



(a) HLU (b) VB (c) VARI

Figure 3-6: SEM micrograph magnitude 2500x

The SEM results showed that the fiber/matrix bonding characteristics of the VARI composite were better than those of the HLU and VB composites. This causes the mechanical properties of the VARI composite to be better than the two composites.

4. Conclusions

Before utilizing GFRP for the production of UAV components, it is essential to acquire an understanding of the mechanical characteristics of the material, which are contingent upon varied manufacturing techniques. Such comprehension is imperative to execute a thorough structural analysis of the UAV in advance of the subsequent phases involves in the manufacturing procedure. Previous studies have assessed the tensile properties of GFRP utilizing several manufacturing techniques, namely HLU, VB, and VARI. Nonetheless, to gain a comprehensive understanding of the material's properties, it is imperative to investigate additional measures such as compressive and shear properties. The experimental test results showed that the compressive strength of the VB and VARI composites was higher than that of HLU by 12% and 71%, respectively. Meanwhile, the compressive strength of the VARI composite was 53% greater than that of the VB composite. Although the compressive strength of the VB composite is higher than that of HLU, the shear strength is different. The shear strength of the VB composite is 9% lower than that of HLU. Meanwhile, the shear strength of VARI composites was higher than HLU and VB by 29% and 42%, respectively.

The results of the study exhibit that the vacuum bagging technique for fabricating composite is better than manual hand lay-up. However, the vacuum-assisted resin infusion technique is the best process to fabricate composite material with liquid resin compared to both techniques. The compressive and v-notched shear properties of the composite become the evidence for this. The compressive and v-notched shear properties of VARI composite are superior to two other techniques. SEM observation indicates that the fiber/matrix bond of the VARI composite is the best compared to both techniques. Further studies on the effect of composite manufacturing techniques using different materials from this study are needed to prove the most influential possibility that causes the shear strength of composite VB to be lower than HLU.

Acknowledgments

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Contributorship Statements

KA analyzed the results and prepared the manuscript; RAP prepared the specimens and performed the experiment; RH prepared the specimens and performed the experiment; RAR prepared the specimens and performed the experiment; TSN prepared the specimens and performed the experiment; RA processed the data and prepared the manuscript; MGPPP processed the data and prepared the manuscript.

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